Intrinsic Birefringence in 157 nm Materials

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Support from SEMATECH

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Birefringence in Cubic Crystals

I. Stress-Induced Birefringence

grown-in or externally applied (mounts, gravity, etc.)

- variable magnitude and orientation (sample-to-sample and within sample)
- weak dispersion visible-UV (NIST-SEMATECH 157 Review 11/00)
- can in principle be reduced to any desired value

II. Intrinsic Birefringence

due to symmetry breaking effect of finite q of photon at short λ

preliminary measurements in CaF_2 (above 157nm and 193nm target values)

- magnitude and orientation fixed by crystal (no sample dep., uniform)
- strong dispersion $\sim 1/\lambda^2$
- CANNOT be reduced! (inherent property of crystal)

(but since fully predictable and symmetric, can be corrected for in principle)

Has been measured in, e.g., Si[1] and GaAs[2]

[1]J. Pastrnak and K. Vedam, Phys. Rev. B **3**, 2567 (1971).

[2]P.Y. Yu and M. Cardona, Solid State Commun. **9**, 1421 (1971).

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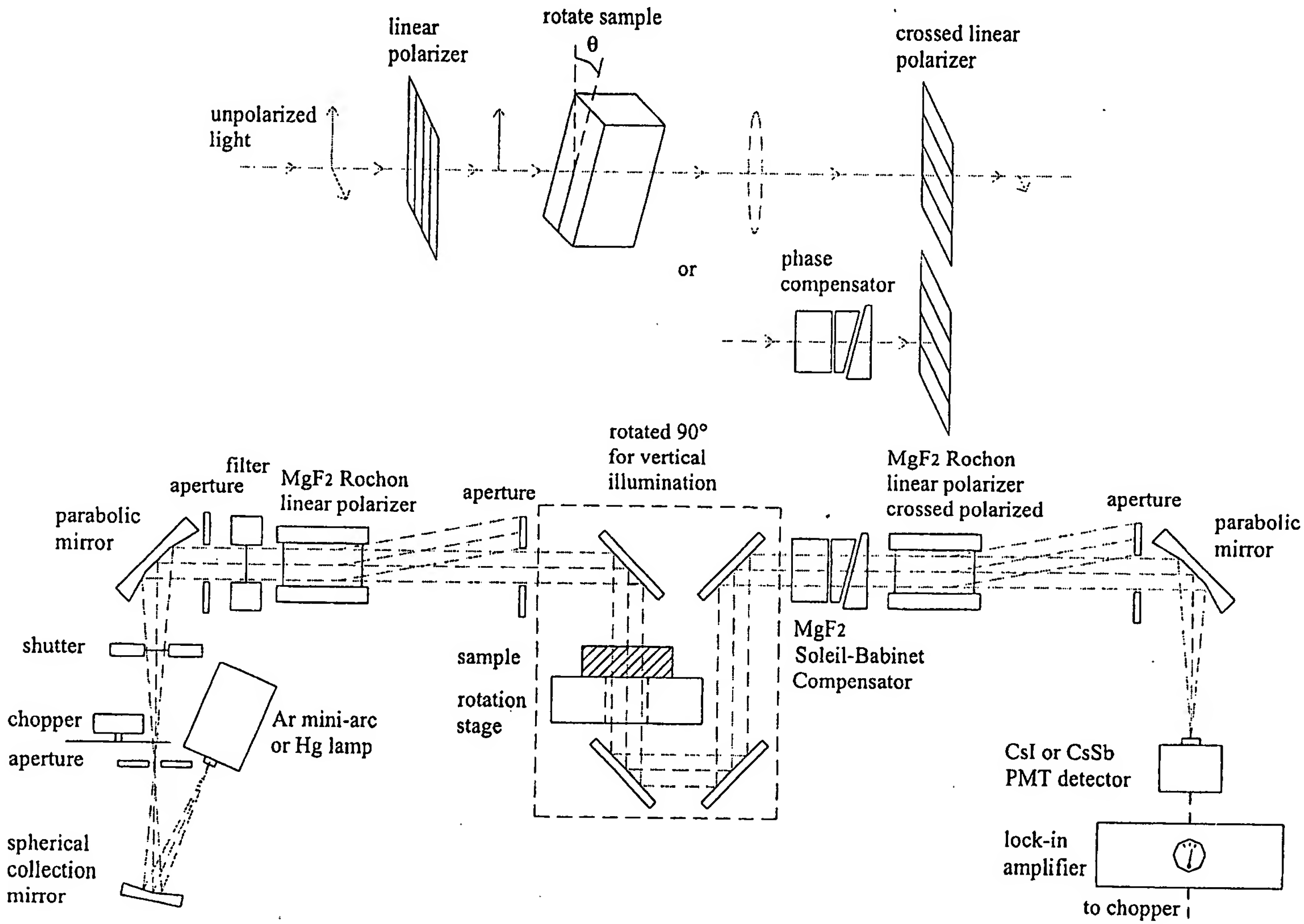
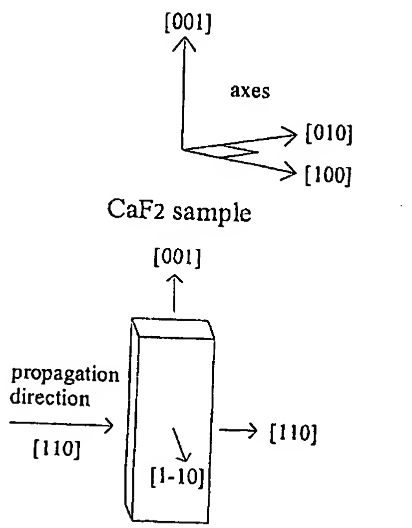
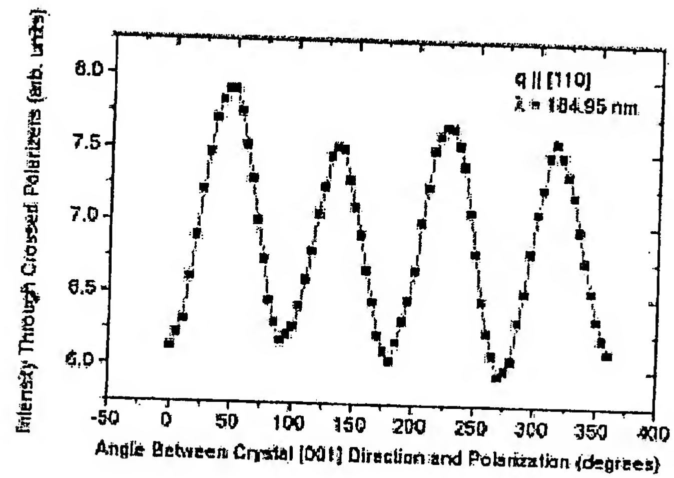
Birefringence Apparatus



Birefringence Measurements at 185 nm

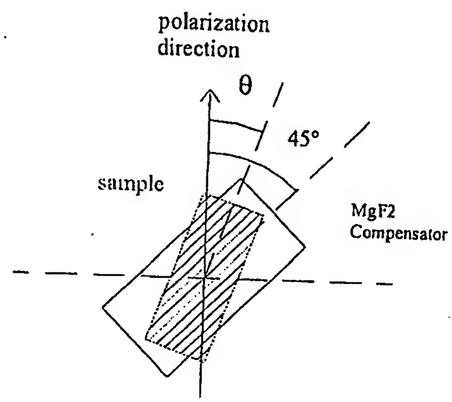
Conventional birefringence in meas. region @ 633nm <0.2 nm/cm

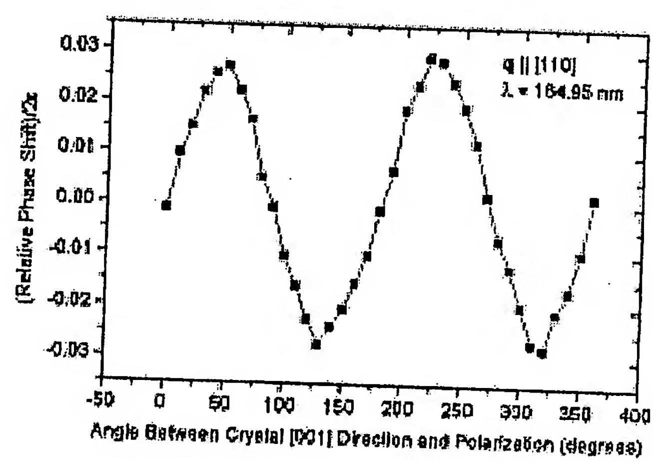




$$I/I_0=\sin^2(\pi d\Delta n/\lambda)\sin^2(2\theta)$$

$$\Delta n = n_{[-110]} - n_{[001]}$$





$$\Delta n = (\lambda/d)(\mathrm{RPS}/2\pi)$$

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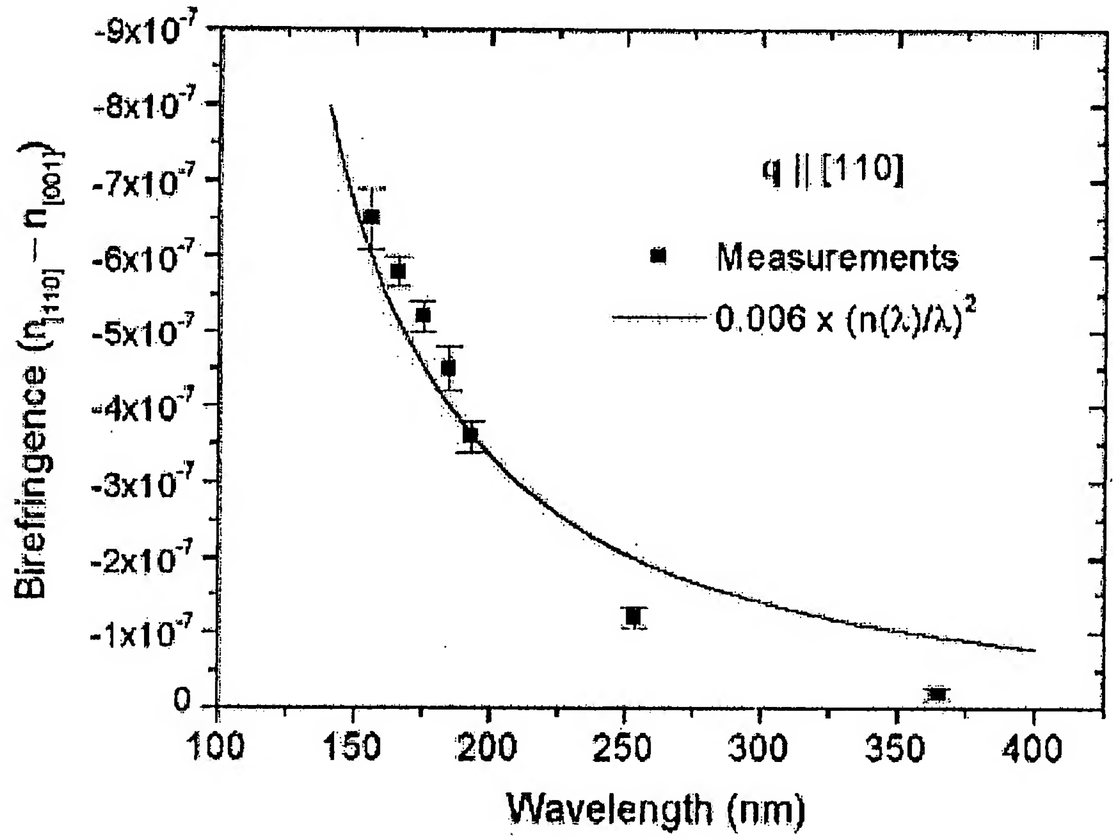
Birefringence Results for CaF_2



Measurements of Birefringence of CaF_2 in the UV

Wavelength (nm)	Line Source	$10^7 \times (n_{<\bar{1}10>} - n_{<001>})$
365.062	Hg I	-0.19 ± 0.08
253.652	Hg I	-1.2 ± 0.1
193.09	C I	-3.6 ± 0.2
184.95	C I	-4.5 ± 0.3
175.19	C I	-5.2 ± 0.2
165.72	C I	-5.8 ± 0.2
156.10	C I	-6.5 ± 0.4

$$\mathbf{q} \parallel [001] \rightarrow \Delta n = 0$$

$$\mathbf{q} \parallel [111] \rightarrow \Delta n = 0$$

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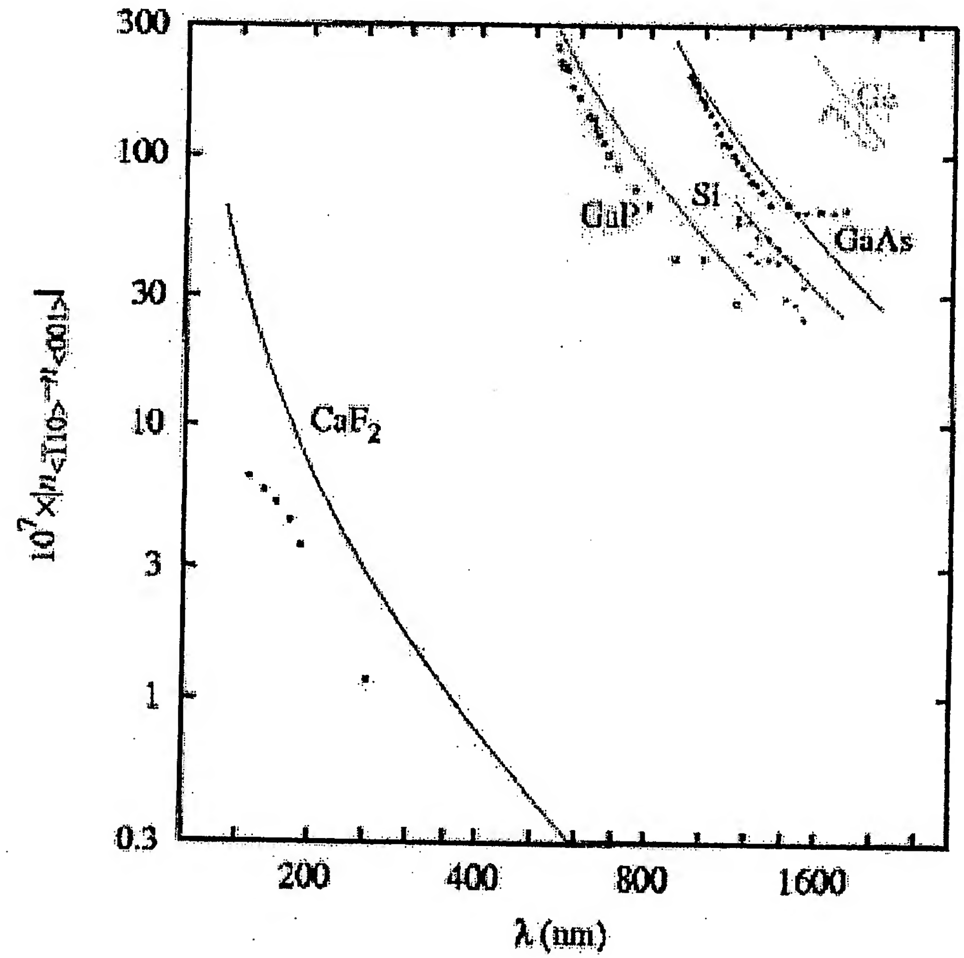
First Principle Calculations

Takes only crystal structure and static dielectric const. from expt.

- for semiconductors, $n_{<-110>} - n_{<001>}$ positive in theory and expt. (meas. by others)
- for CaF_2, $n_{<-110>} - n_{<001>}$ negative in theory and expt.



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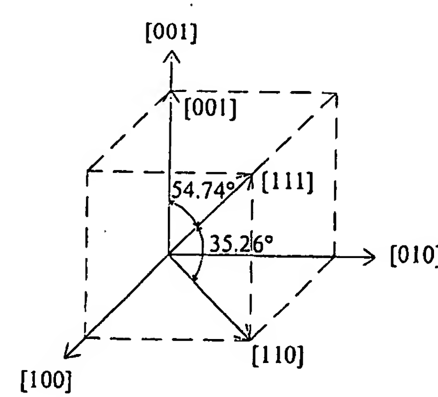
Implications

1) Intrinsic birefringence $\Delta n(157\text{ nm}) \approx 6.5 \times 10^{-7}$ (6.5 nm/cm)
   - exceeds birefringence target value for 157 nm lithography (1 nm/cm) (1st Int. Symp. On 157 nm Lithography, May 2000)
2) Intrinsic birefringence $\Delta n(193\text{nm}) = 3.6 \times 10^{-7}$ (3.6 nm/cm)
   - may exceed birefringence requirements of 193 nm lithography
3) $\Delta n = 0$ for [111] direction (lens orientation)
   - but [110] only $\theta = \cos^{-1}(2/3)^{1/2} = 35.26°$ away
   - concern for high NA systems
4) Good news: effect completely predictable and symmetric
   - thus can correct for in principle
5) Need to know the full angle dependence of the effect
   - fortunately this is completely determined by symmetry alone



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Why Birefringence in Cubic Crystals?

Cubic crystals isotropic if **D** *linearly* related to **E** by 2nd rank tensor

$D_i = \varepsilon_{ij} E_J$ (ε_{ij} dielectric constant) - but assumes λ large

Actually $\mathbf{D} = \mathbf{D}_0 e^{i\mathbf{q}.\mathbf{r}} = \mathbf{D}_0(1 + i\mathbf{q}\cdot\mathbf{r} - (\mathbf{q}\cdot\mathbf{r})^2/2 + \cdots)$ ($q = n2\pi/\lambda$)

(linear term doesn't contribute by symmetry)

$$\varepsilon_{ij}(\mathbf{q}) = \varepsilon(0)\delta_{ij} + \Sigma_{ij}\alpha_{ijkl} q_k q_l$$

Birefringence determined by fourth rank tensor $\alpha_{ijkl} \propto (n/\lambda)^2$

Symmetry seen by $(\mathbf{q}\cdot\mathbf{r})^2$ term - has azimuthal symmetry about **q**

acts like uniaxial stress in direction of **q**

For crystal axes with 3-fold or 4-fold symmetry

effect of $(\mathbf{q}\cdot\mathbf{r})^2$ term is to reduce isotropic to uniaxial

NO birefringence for $\mathbf{q} \parallel$ <111> or $\mathbf{q} \parallel$ <001>

For all other directions $(\mathbf{q}\cdot\mathbf{r})^2$ term results in biaxial birefringence

Further, symmetry breaking component α has only one free parameter

angle dependence determined by $n_{<-110>} - n_{<001>}$ alone!

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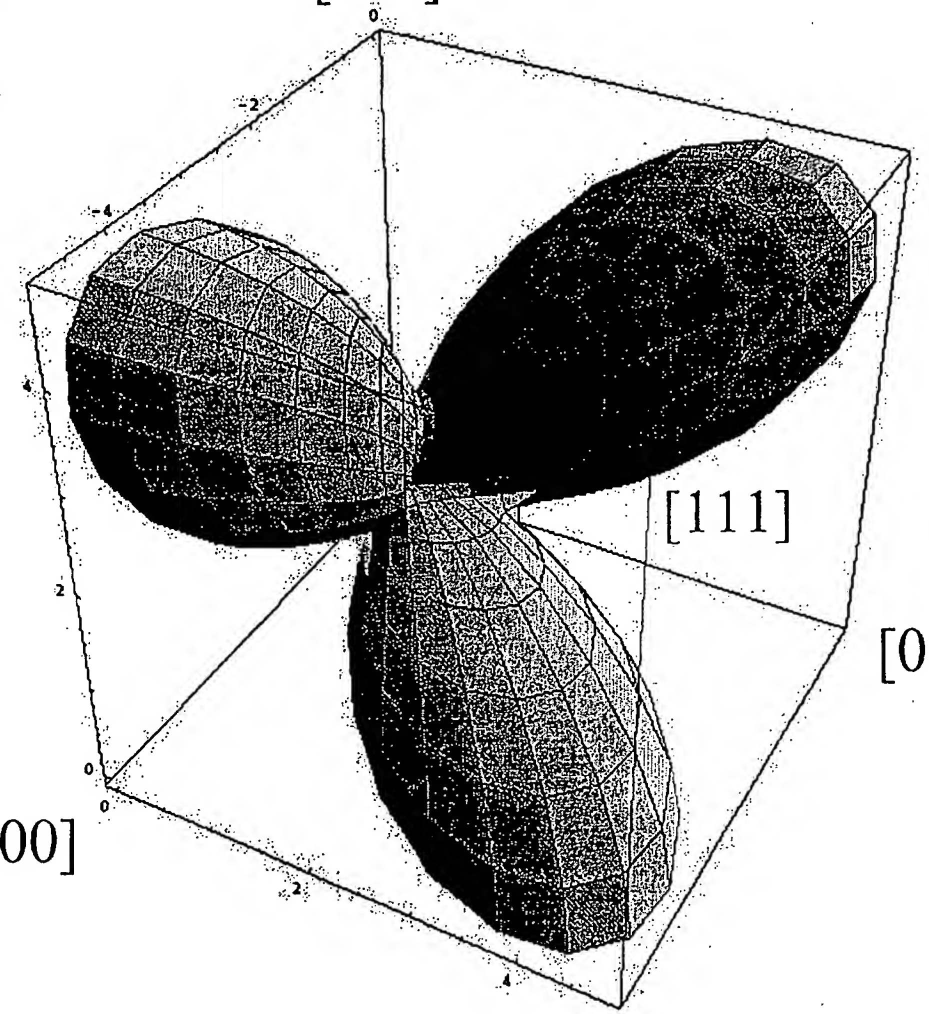
Intrinsic Birefringence

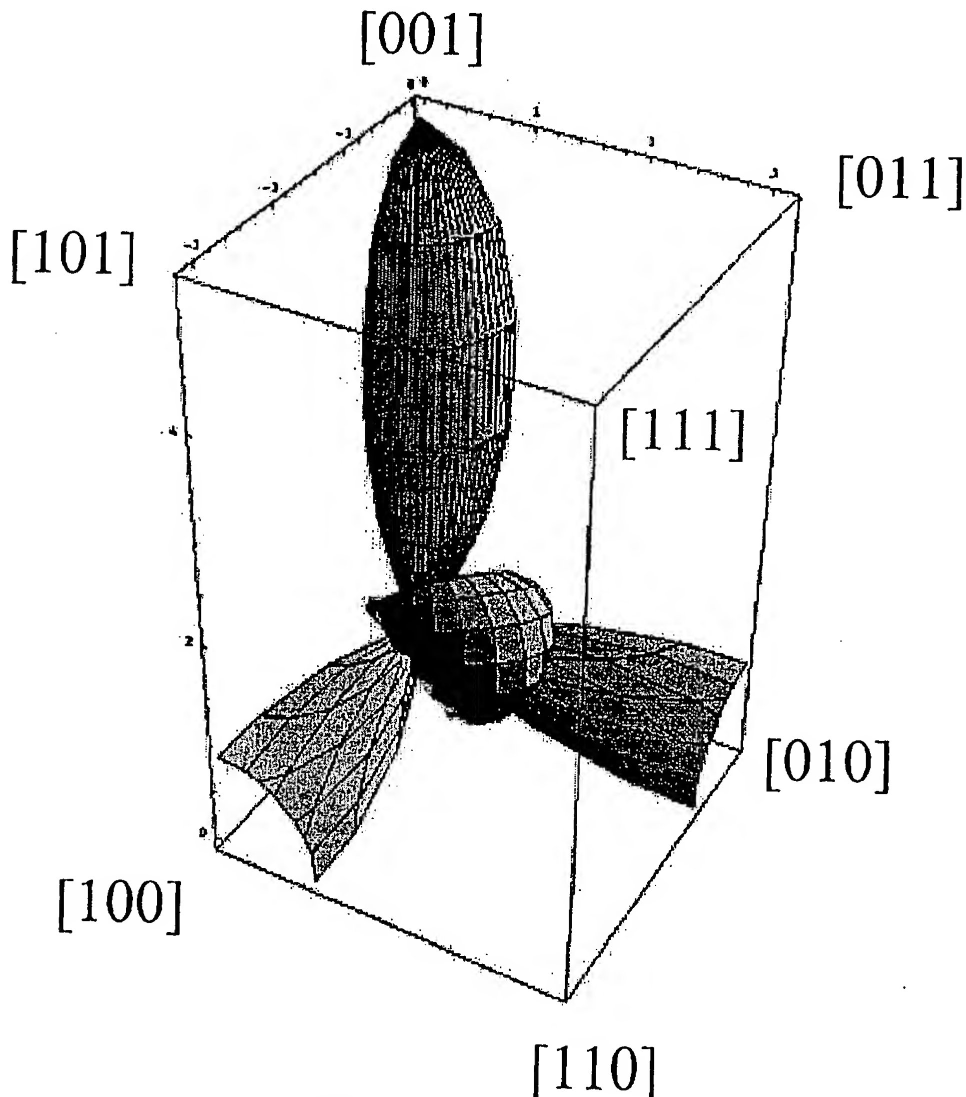
One octant - scaled according to $\Delta n = 6.5 \times 10^{-7}$ for $\mathbf{q} \parallel [110]$

Has 12 lobes



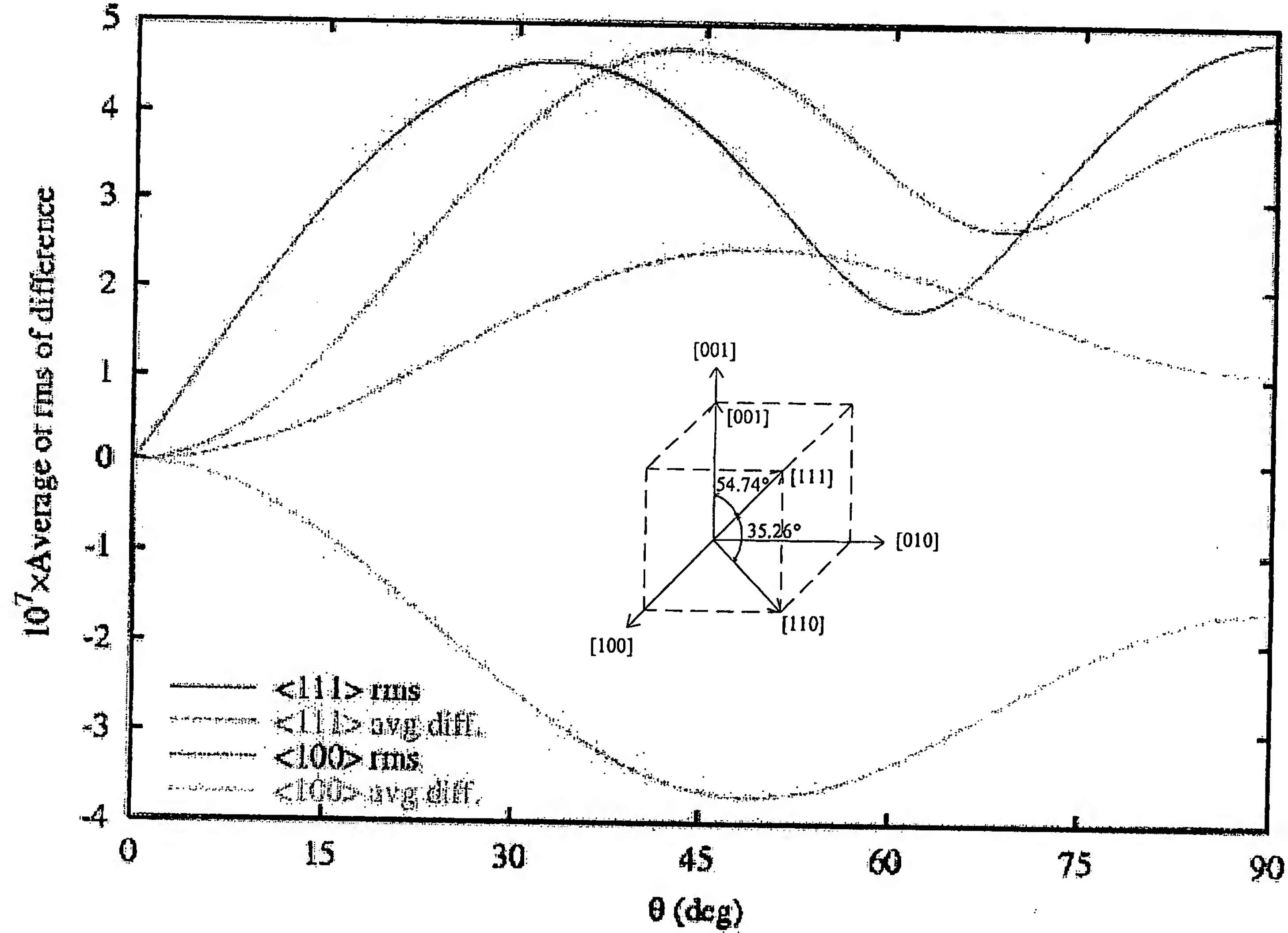
Average Index Variation

One octant - scaled according to $\Delta n = 6.5 \times 10^{-7}$ for $\mathbf{q} \parallel [110]$



Index Anisotropy

Azimuthal average - scaled according to $\Delta n = 6.5 \times 10^{-7}$ for $\mathbf{q} \parallel [110]$



θ is deviation from indicated direction

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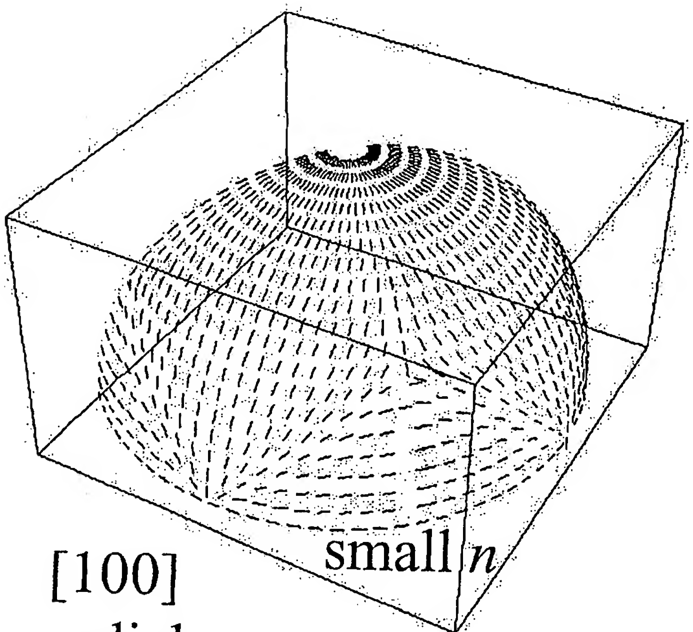
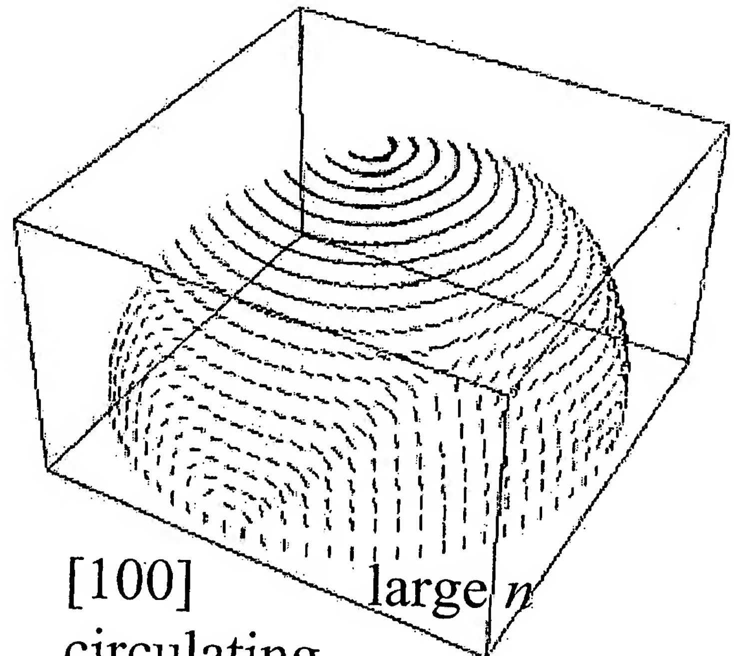
Eigenvector Directions

Shows directions of the two axes of birefringence plotted as a function of propagation direction represented as a point on a sphere. (magnitudes not indicated)



[100]
radial



[100]
circulating

Detailed prescription for full solution available on request

Conclusions

In Summary:

1) There **must** be intrinsic birefringence in CaF_2 (and all cubics)

2) We have calculated the effect

3) Have measured the effect

   $\Delta n = 0$ for q || <111> and q || <001>, as expected by symmetry

   max. value for q || <110>, $\Delta n(157\text{nm}) \approx 6.5 \times 10^{-7}$ (6.5 nm/cm)

   exceeds target value for 157nm (and for 193 nm?) High NA!

4) CANNOT be reduced! Intrinsic to material

   measurements under way for other materials, e.g., BaF_2 and LiF

5) Must live with it!

   But, fully predictable and highly symmetric   can correct for it
   e.g., pair [111] lenses with transverse axes rotated by 60°